Ethics and materials: Some Spanish Cases

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In Navea, north of Spain, a medieval arch bridge shows a visible distortion (fig.1a).[1] A stone falls down from the web of a gothic vault in a big parish church in Burgos (fig. 1b),[2] and a voussoir falls down from the rib of another gothic vault in Oviedo (fig. 1c).[3] An oval dome collapses in Zaragoza, though another four identical domes remain safe (fig. 1d).[4] In the church of Santo Domingo, A Coruña, from the crown of the presbytery arch over the altar, Sunday morning during the mass and the church full of people, the keystone suddenly breaks and a small piece of stone falls over the altar just in front of the priest (fig. 2a).[5] One of the main streets of Pontevedra is closed to the traffic because some cracking has been observed in the vaults of a ruined cloister (fig. 2b).[6] Some tiny cracks are visible on the walls and vaults of the Lonja of Mallorca; an expert writes that these cracks divides the building in four parts which are moving apart like the "drift of the continents" (fig. 2c).[7] In a little baroque church in Lugo, an ashlar vault shows big distortions, is considered at the border of collapse, and several expertises recommend its demolition (fig. 3a).[8] Little domes on aedicules crowning one of the towers in Santiago de Compostela show alarming cracks and displacements of the stones; if they collapse they may fall over the pilgrims on the square below (fig. 3b).[9] The vault of a baroque chapel in Rois, Galicia, collapses and should be rebuilt again, reusing as much as possible the original stones (fig. 3c).[10] The principal arches of a gothic flat vault in Morella, Castellón, yielded with a visible descent of the keystone (fig. 3d).[11]

Sometimes the building has to support new, heavier loads. The ruin of the abandoned (since the 19th Century) monastery of Melón should be consolidated, some vaults are rebuilt and the visitors can walk over them (fig. 4a).[12] A Franciscan Convent is going to be turned into a Cultural Centre, the loads to be supported being multiplied by a factor of two (4b).[13] A little medieval bridge is asked to support the pass of heavy lorries (4c).[14]

These are some of the cases I have studied in the last two decades, all of them referring to questions of structural safety.

These are the kind of situations which often occurs in the field of Historic Structures. They require a study and an answer. This is no scholarly work (though in some cases new lines of future research will emerge). A judgement must be made by the expert and this judgement affects the safety and economy, in the last instance, of people. As there are rarely unique answers, the behaviour of the expert, then, can also be judged as "ethical", if he proposes an intervention that is necessary and adequate (or, recommends no intervention, judging the situation safe), or "non-ethical", if recommends an unnecessary or disproportionate intervention. In relation to the monument, also, the proposal can be judged ethically; any intervention damaging seriously the character of the monument may be labelled un-ethical.

A theoretical frame

Any rational answer must be based in some kind of theory. The theory of masonry structures is, indeed, very old: the Pantheon, Hagia Sophia or the gothic cathedrals were not a matter of chance, a result of blind trial, but of the knowledge of a Master builder. This knowledge was not based in the laws of mechanics and strength of materials, but if we judge for the results, it was a sound knowledge. The knowledge was codified in geometrical rules: the old masters

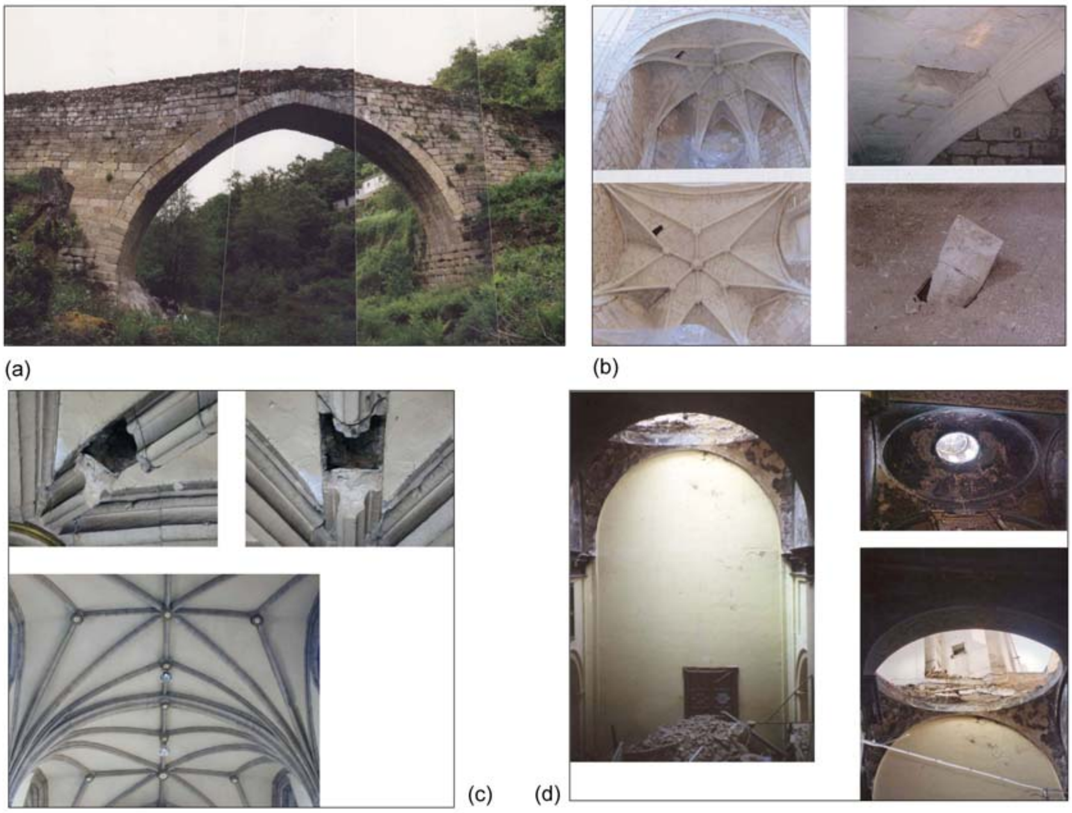


Figure 1

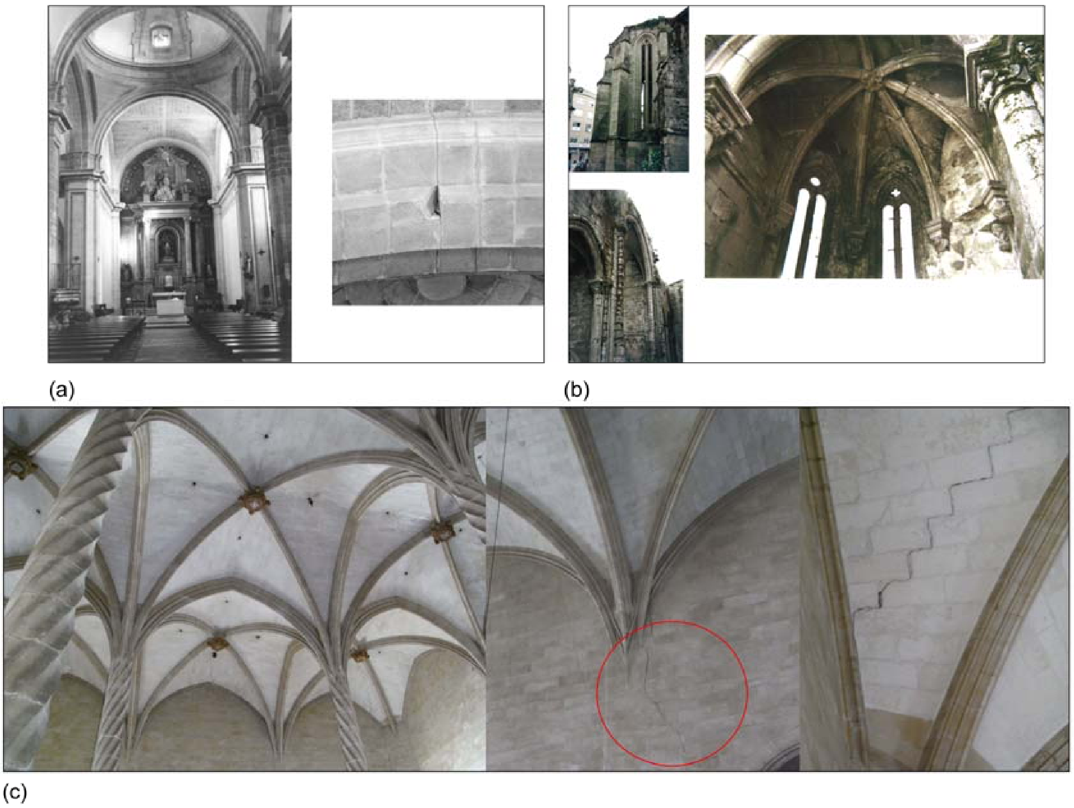


Figure 2

Figure 3

Figure 4

knew that safety is a matter of geometry. We shall see that this is rigorously correct. Could it have been otherwise? Could any modern engineer or architect, any builder, think that structural design was "a vicious circle of ignorance and it remained closed until Galileo cut it"? (Parsons 1976). The extraordinary success of masonry architecture through the ages demands a rational explanation; no contrsuctions stands centuries by miracle.

We will use now the modern theory of structures. However, within the theory of structures there are different lines; the structural equations (equilibrium, material, compatibility) have been written differently depending on the material and the structural type. The classical theory refers to elastic materials and was developed in the 19th Century for bar and framed structures. In many cases the equations of the 19th Century could only be solved then for certain, simplified, cases; only in the second half of the 20th Century the use of computers allowed to solve numerically the equations written more than a Century before.

With the advent of computers and the software to solve the elastic problems, the promise of an "universal tool" to analyze any type of structure was implicitly or explicitly stated. However, in fact the system of (maybe thousands) equations refer to homogeneous elastic materials and, mainly, to bar structures. The popular Finite Element Method programs (linear or non-linear) refers to a continuum divided in "finite elements", but a continuum anyway.

The modern theory of masonry structures

Masonry structures are essentially different from usual modern structures made of steel or reinforced concrete. The usual theory of structures teached in the Schools of Engineering or Architecture is useless to understand the behaviour of masonry architecture.

In fact, a scientific theory of masonry structures developed since the end of the 17th Century (Hooke 1675, La Hire 1695, 1712), was perfected and put to use at the end of the 18th Century (Coulomb) and was used for bridge design during the whole 19th Century. The approach considered the material as discontinuous and looked for equilibrium states in compression. With the arrival of graphic statics (Culmann 1866) engineers and architects were able to obtain easily equilibrium solutions and, eventually, whole complex buildings were analyzed (Ungewitter/Mohrmann 1890).

Of course, the masonry theory was looked with great suspicion by the "cultivated" engineers who considered that only an elastic analysis was truly scientific.

In the first half of the 20th Century a new theory developed: the plastic theory (or limit analysis) emerged as a response to the limitations of elastic analysis. The apparent precision of elastic analysis was demonstrated false when comparing the results of theoretical elastic analysis with the observed deformations in real buildings (England, 1920-1930, under the direction of J. Baker, (Heyman 1998)) Indeed, the system of equations of equilibrium, elastic material and compatibility (boundary conditions) is extremely sensible to very small changes, particularly of the boundary conditions. It was demonstrated as impossible to know the "true" or "actual" state of the structure, as these small changes are unknown and essentially unknowable. The structure is adapting itself to the (unpredictable) changes which inevitably occur during its life.

Two decades of experimental and theoretical work culminated in the 1950's in the formulation of the Fundamental Theorems of Plastic Analysis. The Safe (or lower bound) Theorem solved the problem: a structure is safe if it is possible to find an equilibrium solution which do not violate the yield condition of the material (for example, in a framed structure, the bending moments are less or equal than the full plastic moment). Evidently, elastic analysis is safe, but it is only one among infinitely many equilibrium solutions in a complex hyperstatic structure, and do not represent the "actual" behaviour of the structure.

In 1966, professor Heyman discovered that the Analysis of Masonry structures could be incorporated within the frame of Limit Analysis if the material masonry satisfy certain conditions: masonry is infinitely strength, has no tensile strength and sliding is impossible. A material of this kind is called "standard" and the Fundamental Theorems are true.

The main corollary of the Safe Theorem is that equilibrium analysis is possible (Heyman's equilibrium approach), that is, for usual structural assumptions (small deformations, ductile, stable behaviour), to demonstrate that a masonry structure is safe we only need to find an equilibrium solution with compressive internal forces (this validates the late 19th Century graphical analysis). There is no need to make statements of compatibility. Equilibrium analysis of structures which support mainly its load, lead directly to geometrical statements of the same kind as were used by the old Master builders. The circle, now truly, closes and we are in the situation to understand and make correct judgements which will help us to take decisions.

The modern theory of masonry structures is ignored or questioned today by many engineers and architects, notwithstanding the overwhelming experimental and theoretical evidence. In what follows I will describe briefly the theory with a view of making some remarks at the end about ethical behaviour in relation to masonry structures.

The Material Masonry

The “material” of historic architecture is not simply “pierre” (stone) or “brick”, but stones or bricks plus a certain mortar and bonded in a certain way. We can produce a great variety of masonry using the same stone, from irregular rubble to ashlar masonry, passing through Roman concrete. In Spanish the word for “masonry” is “fábrica”, and it is defined as “any construction, or part of a construction, made of stone or brick bonded with mortar.” We have, then, a material which is a “structure”, from the Latin “struere” which means to pile up things. Besides, certain elements, are also composed of different masonries, Figure 5.

Maybe the best example is the medieval wall (Fig. 5 (b). The wall consisted of an external parament, made of ashlar masonry, and circa one foot thick (25-30 cm); the stone is usually of a certain quality as it must withstand the atmospheric agents (wind, rain, frieze). On the interior, we find another parament, maybe of the same thickness or less, usually built with low quality stone as it is protected. Between both paraments there is a filling. If the wall is, say one meter and a half thick, that means that the filling constitutes two thirds of the wall. This filling is rubble masonry, made with all sorts of stone pieces: the rests of stonecutting, stones with great defects, and, particularly, the rests of the demolition of the previous building. In Spain, we can find within the gothic wall stones of the Romanesque church, the moschee and the Visigoth chapel which existed previously. These “stones” are mixed together filling the interstices with poor lime mortar, many times mixed with earth.

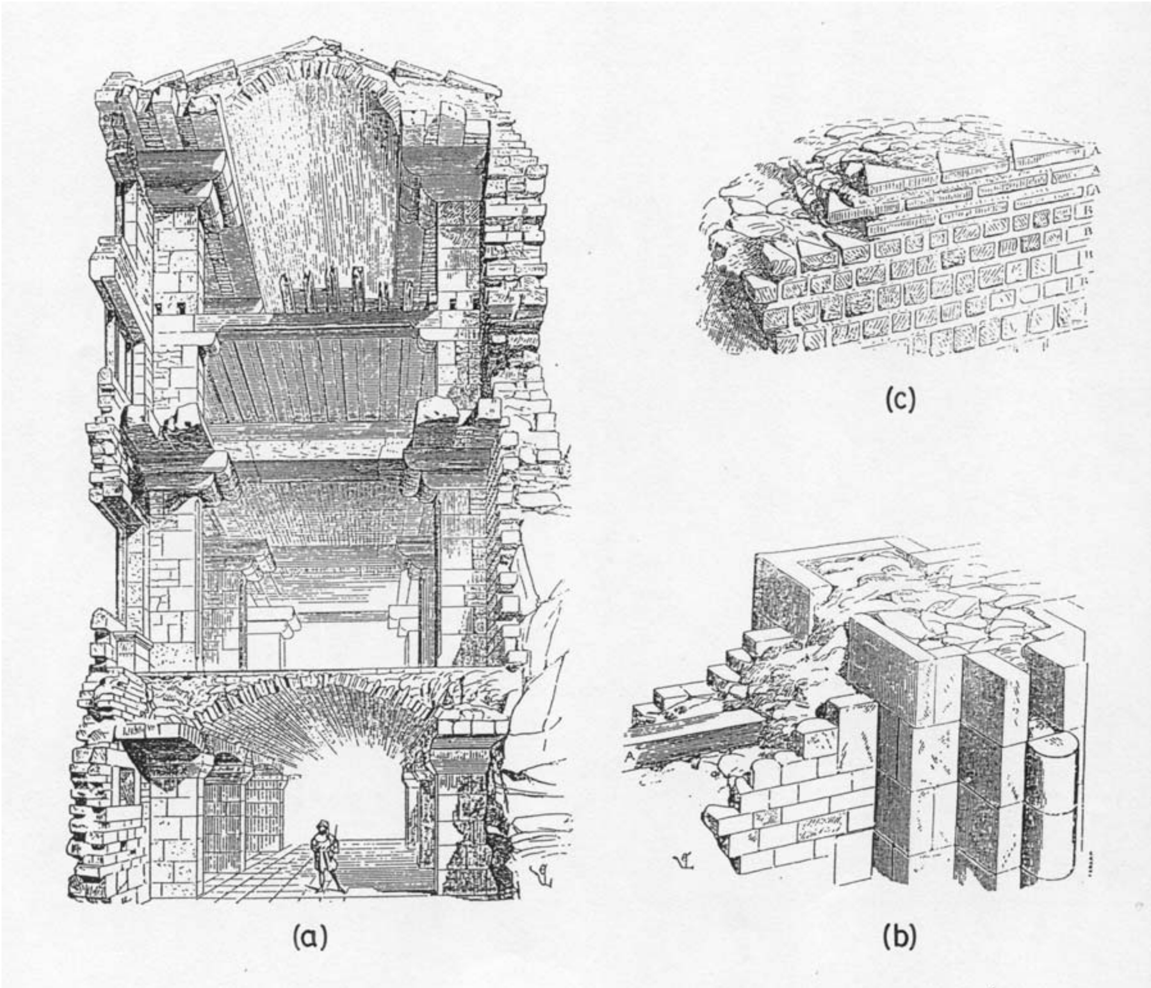


Figure 5
(a) Section through a medieval building; (b) and (c) detail of a roman and medieval wall (Viollet-le-Duc 1858)

The question is: What properties can be assign to such a "material"? In a more pedantic way: What are the constitutive equations? Indeed, any assumptions of continuity, isotropy, the assignment of classical elastic constants (Young's modulus, Poisson's coefficient, etc.), will be, simply, nonsensical. The material is by its own nature discontinuous, irregular, with an unknown (and unknowable) internal constitution, cracked, with different qualities of mortar which present, along the centuries, different levels of "deterioration". Yes, we can test the stones and obtain some characteristics; we may take samples of mortar and do the same... but it will impossible to extract from this data information about the "masonry", the assembly of pieces of stone, broken brick and mortar, plus earth, etc.

However, we need to make some statements about the material if we want to make an structural analysis. The fundamental statement is so "evident" that is many times ignored (though any mason will know!): if we press tow stones we can, indeed, put a lot of pressure; but if we pull, the two stones simply separate. Masonry is a material that must work in compression and has no tensile strength. Individual stones do have tensile strength to maintain their form, but an assemblage of stones has no tensile strength. In addition, we may observe that the friction coefficient is very high and that sliding is very rare.

The next question will be what is the compressive strength of a certain masonry, made of certain stone with a certain mortar. Again, the laboratory test information (compressive strength results for both the stone and the mortar) will demonstrate completely insufficient. It is the “bonding” what has the greatest influence: the size and form of the stones, the thickness of the joints, and, above all, the nature of the joints. Because, the “joint” is rarely an uniform layer of mortar. Masons use small pieces of stone (slate, for example) or other materials (wooden wedges and, I have seen this often in North of Spain, shells of mollusc). The joint is, again, a structure with an unknown constitution.

And what will be the strength of a the column of, say, a Gothic church? An external ashlar parament encloses an irregular rubble filling, as we have seen. We can compute the loads, but what is the stress distribution?

History can help us to understand the situation. At the end of the 19th Century many thousands of laboratory tests were made on stones of any kind. Compressive, tensile and shear strength values (for the stone dry or humid, set following the “quarry face” (“le lit de carriére”) or edge bedded (“de champ”, “en délit”). There were also many tests on mortars, but much fewer on pillars. It is interesting to compare the results of the strength tests with the admissible stress admitted in the Codes of practice. For example, in Warth (1903), for Granite with a compressive strength of 77-240 N/mm², the admissible strength recommended is 3-5 N/mm², with a safety coefficient greater than 20. The usual rule for “good” masonry was to take 1/10th of the compressive strength of the stone. Such big coefficients of safety transmit one message: We do not know and we are afraid.

We may continue with uncountable examples of the vain efforts (at the end of the 19th Century and the story repeats today) of obtaining the strength of historic masonry from the strength of the stone and mortar and the kind of bonding. It is simply impossible.

Fortunately, it is, also, unimportant. The stress levels in masonry buildings are vey low and strength is very rarely a problem. Indeed, the problem of masonry structures is not strength but stability (the buttress should resist the thrust of the vault without a failure by overturning). As we shall see, strength calculations can be very dangerous, because we may be very near the collapse with very low stresses.

Two observations may serve to “prove” that stresses are very low. First, we can use a 18th-19th Century parameter to measure the crushing strength of stone: the height of column of uniform section which will crush at the bottom. The value of this limit height is simply:

$$h_{lim} = \gamma / \sigma_c$$

where γ is the specific weight and σ_c is the crushing strength. For a medium sandstone with γ = 20 kN/m² and σ_c = 20 N/mm², the limit height is 1000 m or 1 km! The many strength tables in construction manuals of the 19th Century included this parameter. In Figure 6 we have one extracted from Collignon.

INDICATION DES MATÉRIAUX.	Poids du décimètre cube.	Charge d'écrasement par centimètre carré.	Hauteur représentative de la charge d'écrasement (1).
Pierres volcaniques.	kilogr.	kilogr.	mètres.
Basalte de Suède.	3,06	1912	6248
Basalte d'Auvergne.	2,88	2078	7215
Lave du Vésuve, dite *Piperno*. . .	2,60	563	2165
Lave grise des environs de Rome.	1,97	228	1157
Tuf de Rome.	1,22	58	478
Granits.			
Granit d'Aberdeen bleu.	2,62	767	2927
Granit vert des Vosges..	2,85	620	2175
Granit gris de Bretagne.	2,74	654	2383
Granit de Normandie, Gatmos. . .	2,66	702	2639
Granit gris des Vosges.	2,64	423	1603
Grès.			
Grès très-dur.	2,52	813	3226
Grès blanc.	2.48	923	3713
Grès bigarré des Vosges.	2,17	400	1843
Pierres calcaires.			
Marbre noir de Flandre..	2,72	789	2901
Marbre blanc veiné.	2,70	298	1104
Marbre rouge du Devonshire.. . .	2,70	522	1933
Calcaire de Portland..	2,42	262	1083
Pierre de Caserte, près Naples. . .	2,72	595	2191
Pierre noire de St-Fortunat (Lyon)	2,65	627	2366
Liais de Bagneux, près Paris. . .	2,44	445	1824
Travertino de Rome.	2,36	298	1262
Roche de Châtillon, près Paris. . .	2,29	174	760
Roche douce de Châtillon.	2,08	134	644
Roche d'Arcueil, près Paris. . . .	2,30	253	1100
Pierre de Saillancourt, 1re qualité.	2,41	141	585
Briques.			
Brique dure très-cuite.	1,55	150	962
Brique rouge.	2,17	57	262
Brique rouge pâle.	2,08	39	187
Mortiers.			
Mortier de chaux et de sable de rivière.	1,63	31	»
Mortier de ciment de tuileau. . .	1,46	48	»
Mortier de pouzzolanes de Naples et de Rome mêlées.	1,46	37	»
Mortier avec chaux éminemment hydraulique.	»	144	»

(a)

Working stress	N/mm²
Buildings	
Columnas de la iglesia de Toussaint d'Angers	4,4
Pilares de la cúpula de S. Genoveva en París	2,9
Pilares de la iglesia de Santa Sofía en Constantinopla	2,2
Pilares de la catedral de Palma de Mallorca	2,2
Columnas de la iglesia de S. Pablo extramuros en Roma	2,0
Pilares de la cúpula de S. Pablo en Londres	1,9
Pilares de la cúpula de S. Pedro en Roma	1,7
Pilares de la cúpula de los Inválidos en París	1,4
Pilares de la catedral de Beauvais	1,3
Base del tambor del Panteón de Roma	0,6
Bridges	
Puente de Morbegno ($L = 70$ m)	7,0
Puente de Plauen ($L = 90$ m)	6,9
Puente de Villeneuve ($L = 96$ m)	5,7
Viaducto de Salcano en Göritz ($L = 85$ m)	5,1
Puente sobre el Rocky River ($L = 85$ m)	4,4
Puente de Luxemburgo ($L = 85$ m)	4,8

(b)

Figure 6
(a)Strength of stones, including a column with the limit height (Collignon 1887); (b) Working stresses in big masonry constructions (Huerta 2004)

The maximum sizes are one or two order of magnitude over the dimensions of even the greatest masonry buildings and bridges. It is to be expected, then, that stresses are indeed very low. In Figure 6 (b) maximum mean stresses in several of these constructions are given. It is remarkable, for example, that Benouville (1891) found in his analysis of Beauvais cathedral an stress of only 1.3 N/mm² at the foot of the columns supporting the highest gothic vaults (48 m). The piers of St. Peter in Rome, supporting the dome with a weight of 30,000 tons, on a drum with a weight of 10,000 tons, plus the weight of the principal arches and pendentives, etc., have a mean stress of 1,7 N/mm². Of course, sometimes the master builders wanted to impress the visitors and built incredibly slender columns supporting heavy weights, as in the church of Toussaint D'Angers where Rondelet calculated a mean stress of 4.4 N/mm².

However, in most cases the stresses are very low and the danger is not the crushing of the masonry but the stability, that is collapse by overturning. The three statements made in the previous part about masonry, infinite compressive strength, no tensile strength and sliding impossible, seem very adequate, and, in any case, can be checked after the analysis.

Equilibrium in compression

The requirement that the internal forces must be compressive forces implies that in very joint the stress resultant must be contained within the masonry. If the thrust approaches the border, then, a hinge tends to form. If we consider the material with infinite strength, the thrust could be applied at the surface of the masonry.

The locus of the position of the thrust for a certain family of sections is called the line of thrust (Fig. 7a). This line is a graphical representation of the equilibrium equations. The material imposes that the line must be contained within the masonry as it appears. When the line of thrust touches the border a "hinge" forms.

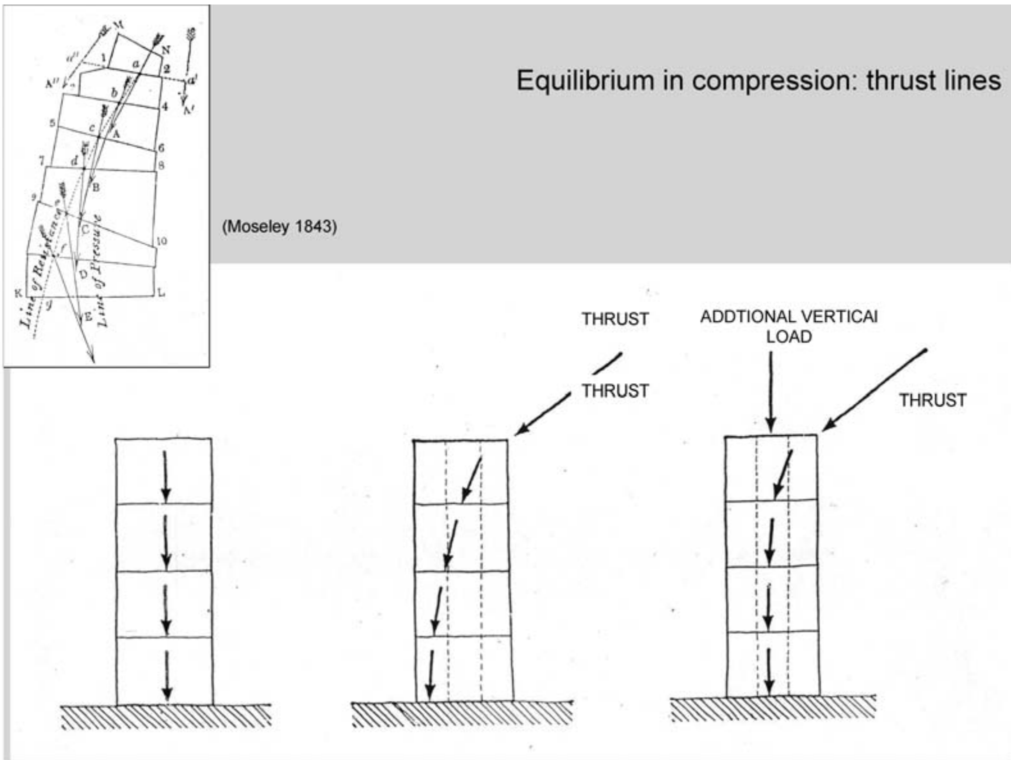


Figure 7
(a) Definition of line of thrust (Moseley 1843); (b) Thrust lines; buttressing by loading (Gordon 1978)

Safety, then, is a matter of geometry: it is achieved if it is possible to draw a line of thrust contained comfortably within the masonry. In Figure 7 (b), in the middle, the wall is in a dangerous situation (any increase of the inclined force on top will produce the collapse), though the stresses at the foot may be very low. Curiously, and against our “common-sense”, safety is achieved increasing the load on the structure. This device of buttressing by loading was well known by the old master builders. It could be that big sculptures or pinnacles crowning the walls or external buttresses have more than an aesthetic function. In fact, it may happen that their temporary removal trigger a collapse.

In a buttress subject to a certain load the line of thrust is unique: we can calculate in every section the position of the stress resultant (however, we will be in trouble if we try to know the stress distribution, which will be greatly influenced by the actual constitution of the joint, the presence of stone wedges, the partial degradation of the mortar, the irregularities of the stone beds, etc.). The buttress is a statically determined (isostatic) structure.

Equilibrium of the arch

With the arch is different. Simple static considerations will show that it is possible to draw infinite thrust lines within the masonry, corresponding to infinite possible equilibrium solutions in compression. The arch is a statically indeterminate, hyperstatic, structure. We can examine briefly the statics. In Figure 8, on the left side, we have an Etruscan voussoir arch. Stones were cut and set on a centring. When the centring is lowered the stones tend to fall down, but, and this is a wonder, the remain in equilibrium. Let us consider the keystone. The weight must be equilibrated by the stress resultants, the thrust, in the joints. De do not know the stress distribution, but we do know that the two thrust must cut the line passing through the centre of gravity of the keystone in the same point (moment equilibrium), that the sum of the vertical components of the thrust must be equal to the weight, and, finally, that the two horizontal components must be equal and with opposite directions. If we establish the equilibrium of the either of the lateral voussoirs, we will see that the horizontal component of the thrust must remain constant, and, in fact, the thrust at the abutments is an inclined force, "the arch never sleeps", always is thrusting against the abutments. The whole line, as we have already said, must be inside the arch.

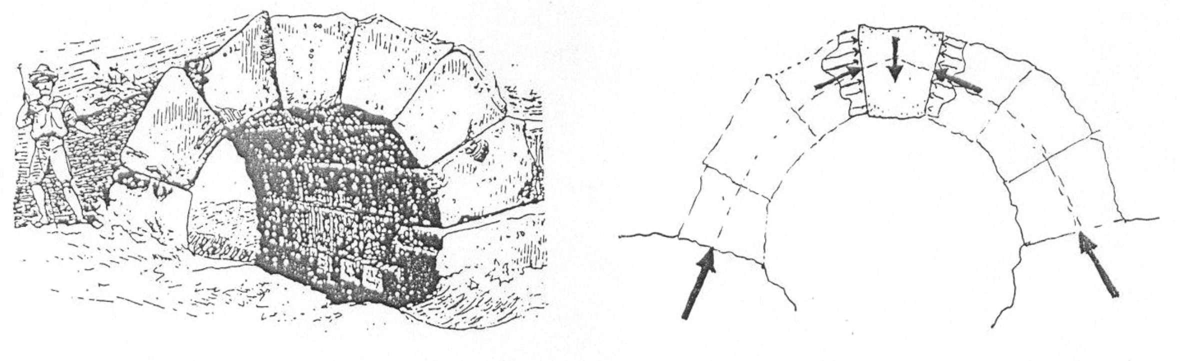
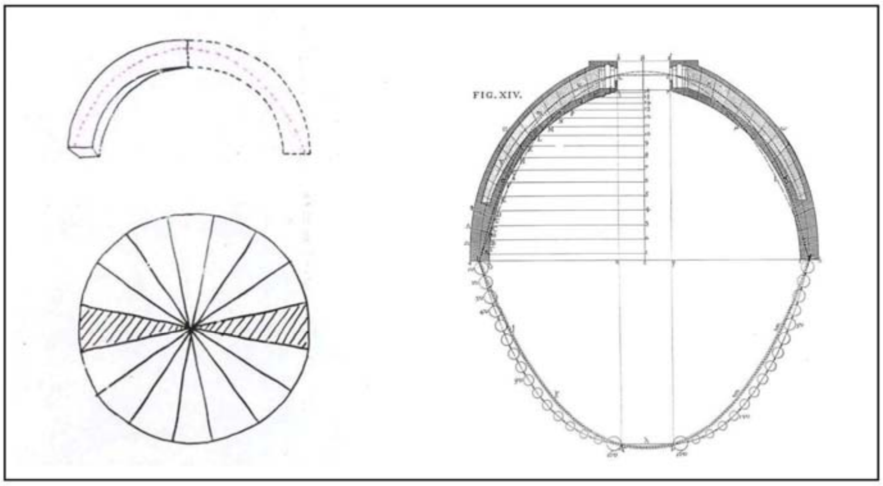


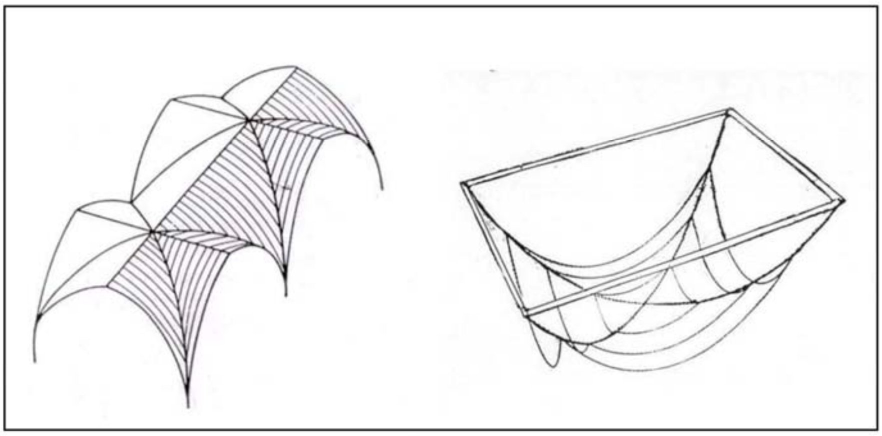
Figure 8
Equilibrium of an arch (Huerta 2004)

Masonry architecture along history has solved two problems: to design an arch which is stable (with a thrust line inside) and abutments which can withstand the inclined thrust of the arch. Byzantine and gothic architects, for example, gave different solutions to the same problem. The history of masonry architecture has been written from the point of view of the vault, but the buttress system is also a fundamental part, in fact, that which supports the whole structure (Huerta 2010).

The study of the equilibrium of more complex forms of vaults can be reduced, thanks to the Safe Theorem, to the study of a system of arches or blocks. Then, we may imagine a dome divided in arches by cutting it for meridian planes. Every two opposed lunes or "orange slices" form an arch; if the thrust line is inside the arch then, the dome divided in arches is stable and, per force, the real dome must be stable. We must keep in mind that we are looking for one, among infinitely many, equilibrium solutions with internal forces inside the masonry. The assumption of zero hoop-forces is arbitrary, but leads to a simple and safe solution, Figure 9 (a). The hanging model of Poleni for St. Peter's illustrates very well the equilibrium of the dome. In the case of a gothic cross vault, we may cut also the barrels into elementary arches which transmit their weight to the diagonal arches and, then, to the springings, Figure 9 (b). Again, a hanging model helps to understand the equilibrium (hanging models were used extensively by Gaudi to design his masonry structures).



(a)



(b)

Figure 9
Static analysis of vaults using the "slicing technique", illustrated by hanging models: (a) Domes (St. Peter's); (b) Cross vaults (Heyman 1995; Poleni 1748)

Cracks

An arch thrust against the abutment (Fig. 8a). The forces are transmitted to the foundations and eventually must be resisted by the soil. To produce the stresses to equilibrate these forces the soil must consolidate; inexorably, it must settle some amount. The arch in the figure must adapt to a certain increase of the span. But the arch is made of “rigid” voussoirs, how is this possible? The arch cracks: a crack form at the keystone, opening downwards, and two other cracks at the springings (in this case) opening upwards, Figure 8b. The cracks can form because of the properties of masonry: very good (infinite) compressive strength, no tensile strength and no sliding. Because of the cracking, the thrust line must pass through the three points of contact of the voussoir (which act as hinges) and its position is fixed. Now, we can obtain the value of the thrust at every joint, the arch is a three-hinged arch, which is a isostatic structure and a perfectly safe structure. In the drawing the increase of span has been exaggerated to make the movement visible but any little yielding of the abutments will produce the cracking, though the crack may be too thin to be appreciated (or even may have been closed by the elasticity if the mortar).

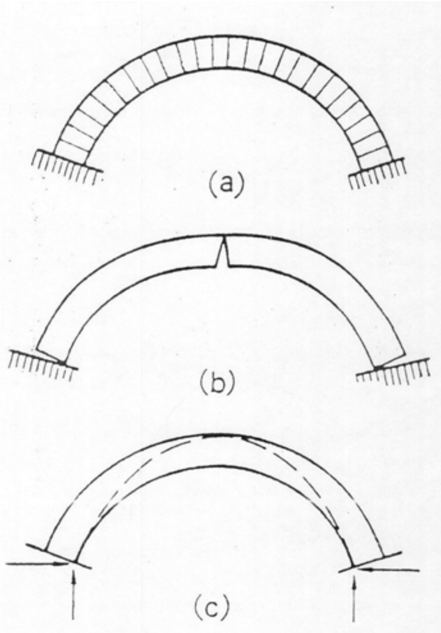


Figure 10
Cracking of a masonry arch due to a small yielding of the abutments (Heyman 1995)

In the front arches in walls or in the transverse arches, the three cracks are clearly visible, Fig. 11 (a). In the case of the barrel vaults of Romanesque or Renaissance churches, the crack at the keystone is clearly visible from the floor, but to see the cracks at the haunches one has to climb to the extrados and, there, maybe remove some of the filling. Many times, the cracks have been closed and the masonry painted so that it is not possible to see them, Figure 11 (b). But the distorted form of the arch is proof of their existence, and, no doubt, most of the thrust is passing through the hinges, the points of contact between the voussoirs. Sometimes, the increase of span is large and the arch or vault is greatly distorted as in Figure 3 (a), above. Now we are able to understand the distortion: the vault divides in two parts which move rotating around the hinges. It is this discrete rotation which produces the distortion, which can not be explained in elastic terms.

(a) (b)

Figure 11
Cracks in arches. (a) Simple arch with visible cracks in Tronchón, Teruel; (b) Distorted transverse arches with the cracks closed in the cathedral of Santiago de Compostela (note the useless bronze cramps added)

Any movement of the abutments will cause a certain pattern of cracks. However, never more than three hinges form, and the arch remain stable, being unaffected by these “small” movements, Figure 12. In every case, there is a different thrust line, that is, a different solution of internal forces in equilibrium with the loads. The changes are drastic: a joint which in one case has a central thrust may have, after a little movement, a hinge.

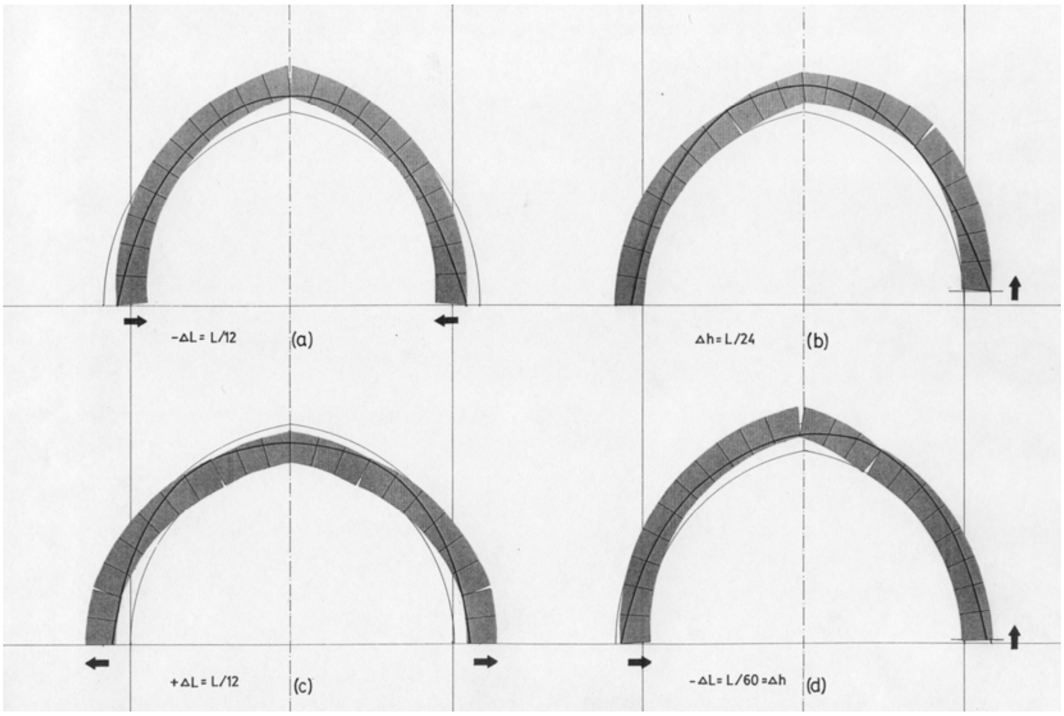


Figure 12
Different patterns of cracking corresponding to small movements of the abutments (Huerta 2004)

Now, the crucial point is this: very small movements of the abutments (changes in the boundary conditions) lead to radical changes in the internal forces. And these movements are impossible to predict. The usual assumption of an arch on rigid abutments (no displacement, no rotation) is just impossible to obtain in practice.

What is, then, the actual thrust line? The question is impossible to answer and is, therefore, nonsensical. There is no “actual” state but a changing state, which adapts at every moment to these small changes in the boundary conditions (not only the initial settlement, but subsequent movements due to changes in the humidity of the soil, a draught, the vibration produced by some big lorry or for a machine, etc.). The arch of a roman bridge 2000 years old, have passed from infinite states of equilibrium, all of the with internal forces inside the masonry. (The cracking of the arch permits to see what Baker had to measure with delicate instruments in frames in the 1920’s; see above.)

Cracking is what gives “plasticity” to masonry. Cracks are not the prelude of the ruin, nor dangerous, they are natural in a no-tension (unilateral) material. The possibility of cracking is essential to the survival of any masonry structure. Besides, cracks give us most valuable information on the behaviour of the structure. In Figure 11, the cracked flying-buttress indicates that the external buttress yielded a little; the movement stopped time ago and the cracks do not affect the structural safety.

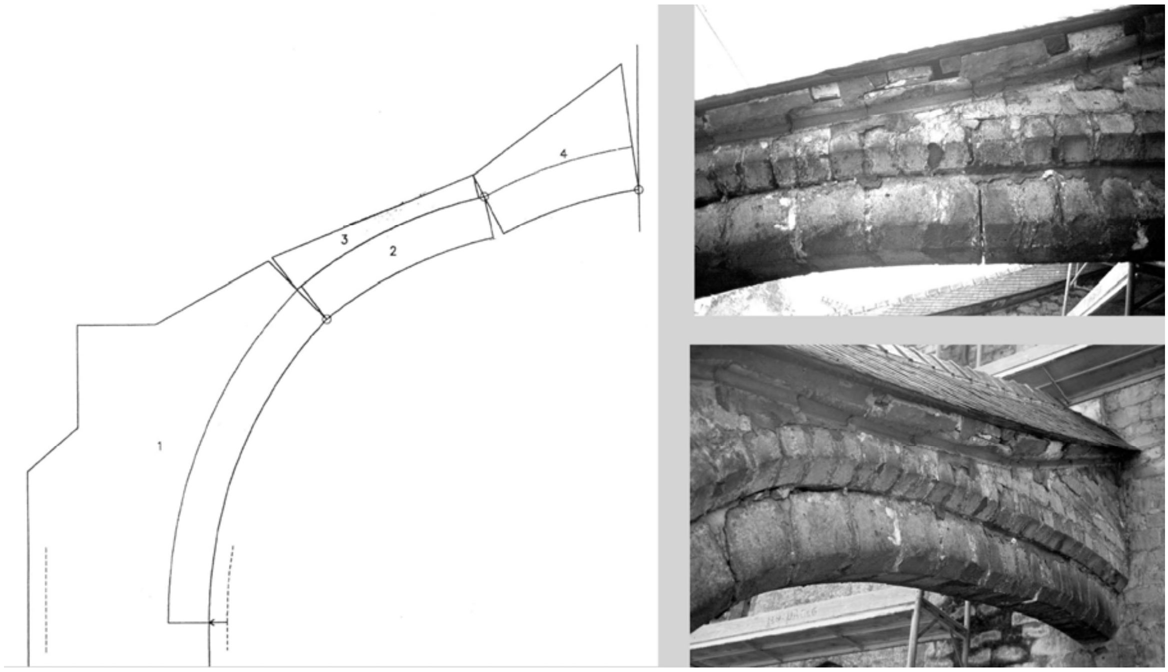


Figure 13
Typical cracking in a flying buttress (Smars 2000)

The different types of vaults have different patterns of cracking. For example, in domes, the usual crack patterns correspond to a small yielding outwards of the dome supporting structure (maybe a drum). This tiny radial displacement will inevitable produce meridian cracks. There is in this part separation of the masonry and no hoop-forces can exist. The cracked part acts a series of arches. Most domes are cracked, though the cracks are usually filled afterwards. However, the expert eye can locate the crack observing, for example, differences in the thickness if the vertical joints among the stones. In other cases, the cracks were covered by plaster. But the cracks are there! and when the plaster is removed to be restored or replaced, "reappear". This happened in the dome of the Pantheon, Fig. 14, when the plaster was removed for restoration at the beginning of 20th Century. Large cracks appeared. It is obvious that these cracks occurred during the period of settlement of masonry and foundations, say, 20 years after the termination of the building. They have been present, though hidden, for more than 1900 years. May we agree that they are not dangerous?

Gothic vaults present also typical cracks. The drawing by Abraham shows the three main types of cracks: keystone cracks, Sabouret's cracks and wall cracks. Heyman has explained their origin as a consequence, again, of a small yielding of the abutment system. These cracks are necessary for the structure to adapt to the "aggression" of the environment, and, as with the cracks in arches and domes, not only are not dangerous, but they give plasticity to the structure. In many cases, the cracks has been filled and covered by plaster, but the eye of the expert will find them.

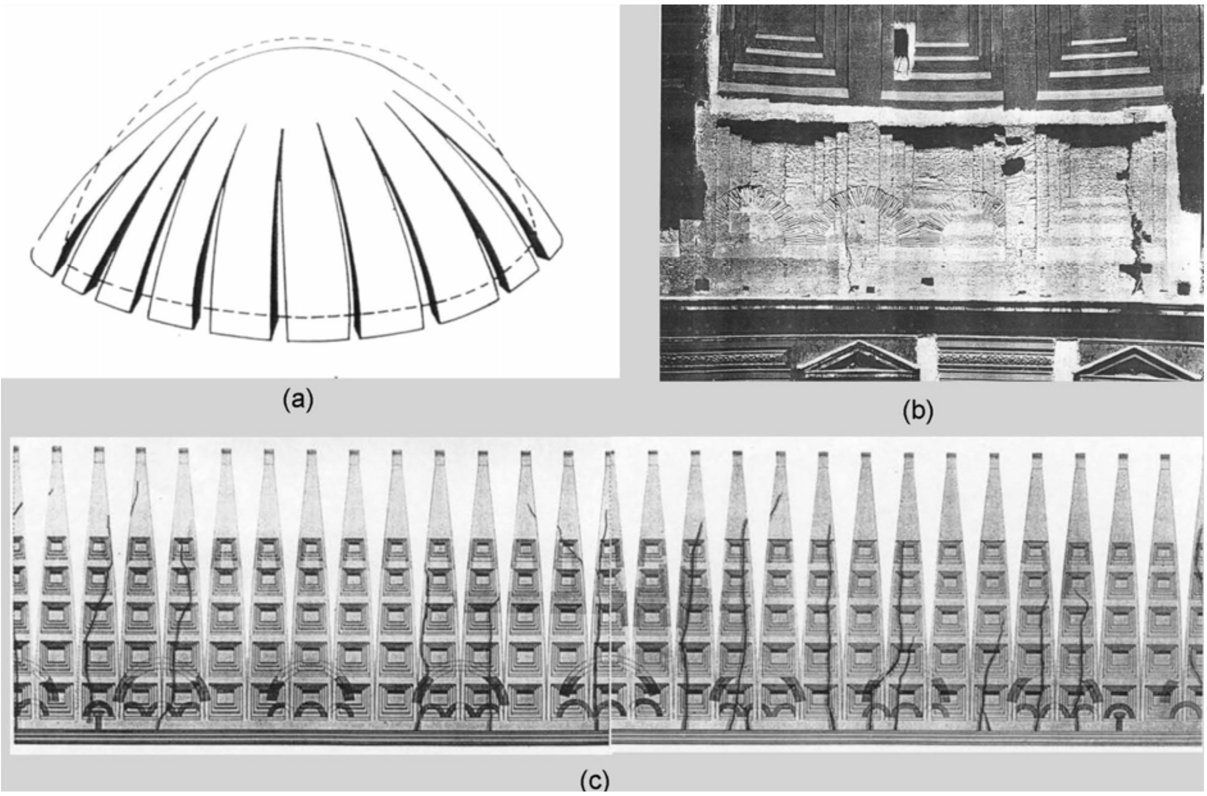


Figure 14
(a) Typical cracks in a dome (Heyman 1995); (b) and (c) Cracks in the Pantheon. The cracks were hidden until the removal of the plaster for restoration (Terenzio 1933)

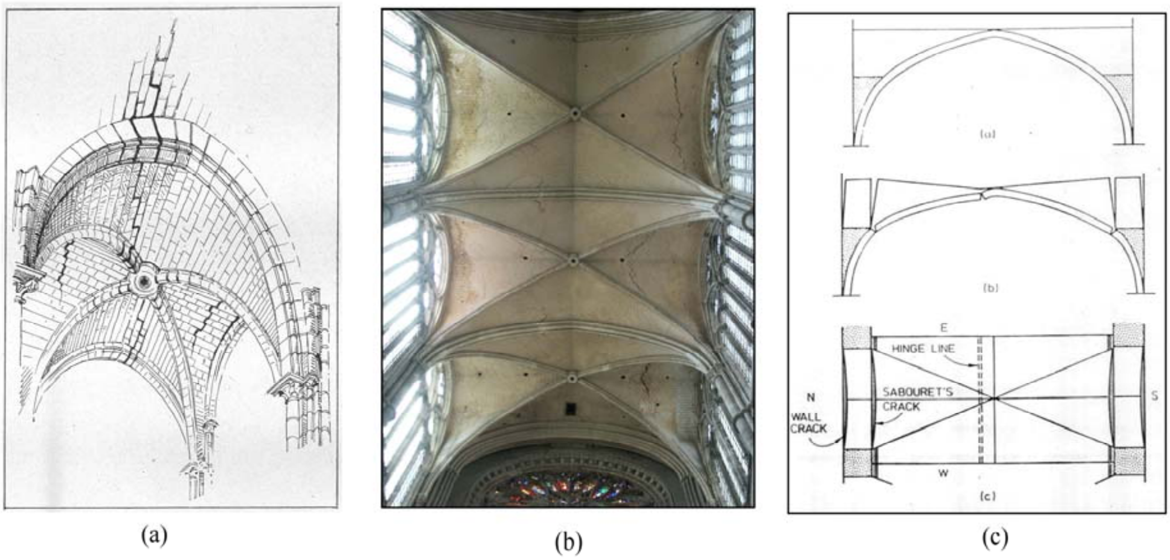


Figure 15
(a) Cracks in gothic cross vaults (Abraham 1934); (b) Cracks in Amiens (photo: I. Tarrío); (b) Explanation of the origin of the cracks (Heyman 1995)

The distortion of the vault may give rise to some local problems, particularly if the vault has suffered abandon and the entry of water. The joints may have deteriorated, the mortar partly disappeared, and, eventually, some stone from the webs or the ribs can fall down. This will not compromise the stability of the vault as a whole, tough it is potentially dangerous to the prayers. In case of doubt, a simple inspection will reveal the potentially dangerous parts. A master mason, working on a light scaffold, will easily "re-position" some stones, replace the deteriorated mortar, even light up some ribs or keystones, so that the vault recovers its geometry and strength.

Any masonry building is, also, cracked. as before, the cracks may be visible, or can be hidden behind an plaster or a new ashlar parament. Viollet-le-Duc expressed clearly (and beautifully) this capacity of masonry buildings to adapt themselves to a changing environment:

> Le squelette cède ou résiste . . . suivant le besoin et la place . . . il semble posseder une vie , car il obéit à des forces contraires et son inmobilité n'est obtenu qu'au moyen de l'équilibre de ces forces.

Fear, Ignorance and Ethics

At the beginning of this contribution we have described some problems of intervention. I believe that now we may have another perspective. There are several possibilities.

It may be that there is no problem at all (the medieval bridge is stable and has been in its distorted form several centuries; the cracks in the Lonja de Mallorca and in Pontevedra are irrelevant); the problem may be local (the voussoir which broke on the presbytery arch had an invisible defect, a "hair", from the quarry); the problem may have been produced by a badly made intervention (the removal of some wooden struts which supported the heavy lantern of the dome in Zaragoza); and, finally, it may be that the situation is serious (there is real danger, the structure can collapse and produce some life losses, as in Lugo or Santiago de Compostela).

In the case of a necessary intervention, there are also some possibilities. It may be that the problem is originated by a concrete factor that can be solved readily with safety and economy of means. But the same problem can be solved at a great expense, making unnecessary studies, dismounting a big part of the structure, putting heavy scaffolds,... Also, the proposed intervention can be respectful towards the Monument, without modifying its nature, or may be aggressive, introducing arbitrarily a big amount of modern materials. In any case, he response may be measured, meditated, or can increase the fear, maybe involving the media (alarming articles in the newspapers or interventions in TV, etc.).

The expert, then, is handling not only a technical problem, but an ethical problem. We may all agree that a big unnecessary intervention is non-ethical. That to solve a non-existent problem is non-ethical. That to promote an expensive invasive intervention when a more cheap and respectful one is possible, is non-ethical. That to involve the mass media to create in the population an alarm, when there is no such an urgency, is non-ethical. It will also be non-ethical not to denounce a really dangerous situation!

Fear

The main problem is fear, and cracks are a good example to gauge the fear and its consequences. We have seen that cracks are natural in a no-tension material. Cracks are "good" because they afford the building the possibility to adapt to the aggressions of the environment. Cracks give, besides, a lot of information with reference to the actual behaviour of the structure.

This contrasts radically with our appreciation of cracks. We labelled cracks as "lesions" or "damages"; we speak of "pathologies", pathology being the study of the diseases.

Old buildings are cracked and, therefore, are "ill", and they require urgent intervention. We try to stop the cracks in many fanciful ways, perhaps "nailing" the crack with cramps (a popular and completely useless intervention which will break the stones). Cracked arches are many times stitched with steel or carbon fibre bars, anchored with Portland cement (before) and, now, with epoxy. The aim is to convert the arch in a monolith which weakens and eventually damage the arch, because reduces or eliminates its plasticity.

In the 1960's-1980's, even today, cracked gothic vaults were often "hanged" from a reinforced concrete shell built over the extrados; in many cases, the individual stones were connected to the shell so as to "hang" actually. The intervention is not only unnecessary, it damages the original structure and destroys the essence of the construction. Today we put strips of Kevlar, glued to the extrados, to afford "bending" strength to the masonry vault.

A cracked building, completely safe, may be the object of intense study, simply because the cracks are interpreted as a sign of danger and of future ruin.

Ignorance

The origin of the fear which cracking produces lies in our ignorance of the true nature of masonry. There are no excuses for this ignorance. Cracks were considered as something normal by all the writers on architecture and construction. Only in very special cases, like in St. Peter's, the cracking caused some concern.

As we have seen the theory of masonry arches and vaults is three hundred years old. The modern theory which explains the crucial role of cracking in the plasticity of masonry buildings is already fifty years old.

We may enunciate a law, analogous to the sentence cited by Tredgold (1831) with reference to the ignorance of practice of some engineers (mainly French): "the stability of a building is inversely proportional to the science of the builder". Paraphrasing this, we may say: "the knowledge about masonry structures is inversely proportional to the fear to cracks".

The main problem is, then, ignorance. The origin of this general ignorance is that modern structures are essentially different to historic structures. The theory of masonry is not teached in the engineering and architecture schools. The tradition of masonry construction is almost completely lost.

The reaction to fear is, following our survival instinct, "defensive". When we feel some danger, it may be "aggressive". We see in many interventions today the consequences of both responses. Suddenly, buildings which have stood for centuries with minimal maintenance are in imminent danger. However, the force of gravity has not changed sensibly, nor the usual loads of wind, snow, etc. It also does not appear that the seismic risk has increased.

The tempo of a big substantial maintenance intervention was, historically, around 100-150 years. In the Pantheon, the previous intervention to that of Terenzio was ca. 1750; Piranesi draw the rotating scaffold for the restoration of the intrados y represented the hidden relieving arches at the springing. It is significant that he draw no cracks!

Thanks to the high-tech approach of intervention, we have divided this tempo by a factor of five. Anyone working in restoration is repairing buildings which were repaired 20 years ago and it is not uncommon that part of the intervention is trying to remove the "reinforcement" added before.

Ethics

We have, then, a problem of ethics. We must change our attitude to historic masonry buildings, increasing our knowledge about them. If the reaction to ignorance is fear, the reaction to knowledge is respect and appreciation. This knowledge is contained in the old architectural and engineering treatises, has survived partially in certain masonry circles, and is evident in the buildings themselves. This knowledge allowed the maintenance of historic architecture for centuries or millennia. There are a lot of arguments in favour of the use of traditional techniques whenever possible. Modern techniques should be used with moderation.

Finally, we should mention a taboo topic in restoration: the problem of money. This is also a big business, like urban planning or residence construction, which moves huge amounts of money. In many occasions, the experts working on this field suffer a lot of direct or indirect pressure to make great, massive, expensive, interventions.

We should be aware that is not uncommon that a cocktail of "ignorance, fear and greed" occurs. It should be counteracted by knowledge, respect and responsibility, the goal being always the adequate maintenance and care of our monuments.

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Notes

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